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QUINTESSENCE IN ADVANCED GRAVITY WAVE EXPERIMENTS*

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Recent observations of distant type Ia supernovae light-curves suggest that the expansion of the Universe has recently begun to accelerate. A popular explanation of present accelerating expansion of the Universe is to assume that some part Ω_Q of the matter-energy density is in the form of dark component called "the quintessence" with the equation of state $p_Q = w\rho_Q$ with $w \geq -1$. Determining the cosmic equation of state is, therefore, one of the greatest challenges of modern cosmology. Future generation of interferometric gravitational wave detectors is hoped to detect the final stages of binary inspirals. The sources probed by such experiments are of extragalactic origin and the observed chirp mass can be translated into the redshift of the source. Moreover, the luminosity distance is a direct observable in such experiments. This creates the possibility to establish a new kind of cosmological tests, supplementary to more standard ones. In this paper we review the standard methods of probing the dark energy, introduce the basic concepts underlying the utility of advanced LIGO type interferometric experiments in making cosmological inferences and we extend some recent results in this respect to the case of z varying equation of state.

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1. Introduction

The story of the Quintessence has its forerunners in the problem of Dark Matter in the Universe (for a review see [1]) as well as in the appeal of the inflationary scenario predicting $\Omega = 1$. Current estimate — based on the results of the Hubble Key Project — of the fraction of critical density contained in clumped matter (*i.e.* including the dark halos of the galaxies) is [2]: $\Omega = 0.33 \pm 0.037$. On the other hand the evidence for spatially flat Universe $\Omega_0 = 1$, has recently been reinforced by cosmic microwave background (CMBR) experiments BOOMERANG and MAXIMA [3]. The most popular explanation of this discrepancy was to associate the missing fraction of $0.7\Omega_0$ with the cosmological constant attributable to the energy density of quantum vacuum. Straightforward calculations thereof resulted in an estimate exceeding the needed value by a factor of about 10^{55} creating the question of why (and how) the cosmological constant now is so small (the problem known as the fine tuning problem).

Recent distance measurements from high-redshift type Ia supernovae [4,5] suggest that the Universe is presently accelerating its expansion. A popular explanation of this phenomenon is to assume that considerable amount $\Omega_Q \approx 70\%$ of the matter-energy density is in the form of dark component called "the quintessence" (also referred to as "dark energy").

There are many theoretical realizations of the "quintessence" from the oldest idea of dynamical scalar field of Ratra and Peebles [6], its modern versions of slowly rolling down scalar fields tracking the evolution of the scale factor in an appropriate way [7], supersymmetric models [8] up to the ideas associated with large extra dimensions [9].

Fortunately, even though we do not know the details of the underlying theory we are able to characterize the quintessence phenomenologically as a cosmic fluid with an equation of state $p_Q = w\rho_Q$, where $w \geq -1$ [10, 11].

If one takes seriously the idea that quintessence is associated with an evolving scalar field then the effective equation-of-state reads:

$$w(t) = \frac{p_\varphi}{\rho_\varphi} = \frac{\frac{1}{2}\dot{\varphi} - V(\varphi)}{\frac{1}{2}\dot{\varphi} + V(\varphi)}\,. \tag{1}$$

Hence there is no reason not to believe that cosmic equation of state could be time dependent *i.e.* $w = w(t) = w(z)$.

Consequently, there are three main goals of observational cosmology as far as the quintessence is concerned. First — based on the data at moderate redshifts — to determine w in the equation of state (its present value). Second, to estimate the $w(z)$ dependence. And third to reconstruct the scalar field potential $V(\varphi)$ or some other parameters of the underlying theory in the case when scalar field is not an ultimate explanation of the dark energy.

In the present paper, on the background of known methods of testing cosmological models, a new class of tests will be presented in the context of quintessential cosmologies. This new class derives from the possibilities and performance of the next generation of gravitational wave experiments.

2. Methods to probe the dark energy

As outlined in the Introduction the presence of dark energy in the Universe is inferred directly from the accelerated expansion of the Universe, and indirectly, from measurements of cosmic microwave background radiation (CMBR) anisotropy. Dark energy contributes about 70% of the critical density, is very smoothly distributed, and has large negative pressure. Its nature is unknown but has observable consequences from its effect on evolution of the expansion rate of the Universe. This in turn affects the age of the Universe [12], growth of density perturbations [13], and can be probed by the classical kinematic cosmological tests.

In the framework of standard Friedman–Robertson–Walker cosmology dynamics of the spacetime is captured in temporal behaviour of the scale factor $a(t)$. Then, one of the field equations determines the Hubble function $H = \frac{\dot{a}}{a}$ at an epoch corresponding to redshift z:

$$H^2(z) = H_0^2(\Omega_m(z) + \Omega_Q(z)) \,, \tag{2}$$

where H_0 denotes the present value of the Hubble function (also referred to as a Hubble constant), $\Omega_m(z)$ and $\Omega_Q(z)$ are the fractions of critical density $\rho_{cr} = \frac{3c^2H_0^2}{8\pi G}$ contained in clumped matter and quintessence, respectively. This equation is supplemented with dynamical equations for energy densities of matter and the quintessence:

$$\begin{aligned} \dot{\rho_m} &= -3H(t)\rho_m \,, \\ \dot{\rho_Q} &= -3H(t)(1+w)\rho_Q \,, \end{aligned} \tag{3}$$

which can easily be integrated after switching from t to z in the role of independent variable (we assume $w =$const. — the general case $w(z)$ is a simple generalization of our considerations). Then the equation (2) reads:

$$H^2(z) = H_0^2 \left(\Omega_m \, (1+z)^3 + \Omega_Q \, (1+z)^{3(1+w)} \right) \,, \tag{4}$$

where by Ω_m and Ω_Q we have denoted present values of relative contributions of clumped matter and quintessence to the critical density. The formula (4) is a starting point for observational tests of the quintessential Universe.

As it is well known [14], one can distinguish three types of distances in Friedman–Robertson–Walker geometry:

(i) proper distance:

$$r(z) = \int_0^z \frac{dz'}{H(z')}\,, \tag{5}$$

which is the coordinate distance in FRW geometry,

(ii) luminosity distance:

$$d_L(z) = (1+z)r(z)\,, \tag{6}$$

which relates the luminosity $\mathcal{L}$ and observed flux $\mathcal{F}$ of the source by the well known formula: $\mathcal{L} = 4\pi d_L(z)^2 \mathcal{F}$,

(iii) angular diameter distance:

$$d_A(z) = \frac{r(z)}{1+z}\,, \tag{7}$$

which relates the comoving linear size D of an object with its observed angular size θ — $D = d_A(z)\theta$.

Since important cosmological parameters like the Hubble constant H_0, Ω_m and Ω_Q are present in the expressions deflning $H(z)$, $r(z)$, $d_L(z)$ and $d_A(z)$, observational determination of the above mentioned distances as a function of redshift could in principle allow one to extract cosmological parameters.

There are three classical test of observational cosmology. First is the so called Hubble diagram $m(z)$ which is of great utility if we have a source population of standard candles *i.e.* the objects with known intrinsic luminosity. Then the observed stellar magnitude of such source translates into luminosity distance: $\log d_L(z) = 0.2(m-M) - 5$ where M is the absolute stellar magnitude *i.e.* the magnitude the source would have, had it been located at the distance of 10 pc. In fact, the case for accelerating Universe provided by the SN Ia surveys was based on this line of reasoning.

Second class of tests dates back to the paper by Alcock and Paczyński [15] who noticed that if we had spherical objects of diameter D and compare their angular diameters $\theta = \frac{D}{d_A(z)}$ with their redshift extents $\Delta z = (1+z)H(z)D$ we can infer the combination $H(z)r(z)$ in which important cosmological information is encoded. In order to implement this method one should have a uniform sample of spherical objects and be able to control the effect of peculiar velocities affecting Δz. Original proposal was to consider clusters of galaxies, modern versions of this approach made use of correlation functions of the Lyman-α clouds seen along the lines-of-sight of neighboring high-redshift quasars [16].

The last group of classical tests is based on number counts of certain objects (galaxies, cluster of galaxies, lensed quasars *etc.*) per redshift interval Δz seen within a solid angle $\Delta\Omega$. This quantity depends on the comoving volume element $\frac{\Delta V}{\Delta z\,\Delta\Omega} = \frac{r^2(z)}{H(z)}$. The interpretation of number counts is heavily biased by the source evolution effects.

More detailed discussion of cosmological tests aimed at elaborating the optimal strategy for probing the quintessence can be found in a recent paper by Huterer and Turner [17]. There is, however, one important remark worth quoting from their study. Namely, if one compares the relative sensitivities of classical techniques of observational cosmology, with respect to w coefficient in the cosmic equation of state, it turns out that these tests (more precisely — the observables extracted in the tests) have peak sensitivities at moderate redshifts $0.5 < z < 1$. It is a typical feature of the quintessential Universe: at high redshifts it is matter dominated and at very low redshifts $z \approx 0$ universal Hubble law dominates the picture.

Since all cosmological observables depend on a number of *a priori* unknown parameters, it is desirable to fix as many of them as possible by alternative methods (*e.g.* to determine H_0 and Ω_m in alternative way). Also because cosmological tests are usually plagued by various selection effects like source intrinsic properties and evolution, reliability of models used *etc.* it is advantageous to look after new classes of test for probing the quintessence. In the next section we shall present one of such new test based on the (simulated) properties of catalogs of events expected to be seen in gravitational wave experiments. In the context of quintessential Universe this idea has been formulated by Biesiada in a recent paper [18] and independently by Zhu *et al.* [19].

3. Advanced gravity wave experiments and the quintessence

The existence of gravitational waves has been predicted by Einstein in the early years of General Relativity. In the seventies their existence has been proven indirectly after accurate measurements of secular orbital period changes in Hulse-Taylor binary pulsar [20] which were found to be in perfect accordance with General Relativistic predictions of energy loss rate from the system due to emission of gravitational waves. Besides providing the model testing site for General Relativity (and alternative theories of gravity) binary pulsars are remarkable in one other aspect — namely they prove the existence of a special class of dense compact binaries which will end their lives in a catastrophic coalescence events.

Laser interferometric gravitational wave detectors developed under the projects LIGO, VIRGO and GEO600 are expected to perform a successful direct detection of the gravitational waves. Inspiralling neutron star

(NS–NS) binaries are among the most promising astrophysical sources for this class of experiments [21]. Inspiralling NS–NS binaries are exceptional sources becasue the luminosity distance to such merging binary is a directly observable quantity easy to obtain from the waveforms. This circumstance made it possible to contemplate a possibility of accurate measurements of cosmological parameters such like the Hubble constant, or deceleration parameter [22–24]. In particular it was pointed out by Chernoff and Finn [22] how the catalogues of inspiral events can be utilized to make statistical inferences about the Universe. In the similar spirit we will discuss the possibility to constrain the quintessence equation of state from the statistics of inspiral gravitational wave events.

The waveform from the NS–NS inspiral event reads:

$$h(t) = \frac{\mathcal{M}}{r}(\pi \mathcal{M} f)^{2/3} \exp\left(i\, 2\pi \int^{t} f(t')dt' \right) \Theta\,, \tag{8}$$

where $\mathcal{M} = \mu^{3/5} M^{2/5}$ is the so called chirp mass, μ and M denote the reduced and total mass respectively, r is the distance to the source and Θ accounts for relative orientation of the detector and the binary system (for details see [25]). Frequency of emitted waves is non-stationary — during the last stages of the evolution of the system it experiences the drift according to the formula:

$$f(t) = \frac{1}{\pi \mathcal{M}} \left(\frac{5}{256} \frac{\mathcal{M}}{t_0 - t} \right)^{3/8} . \tag{9}$$

It has been an old idea of Schutz [26] that from the waveforms and the frequency drifts one should be able to extract the distance to the source and the chirp mass of the system.

This idea has been reformulated [22–24] in the cosmological version by taking into account that in the observers' rest frame the frequency is equal to $f_{\rm obs} = \frac{f}{1+z}$ and because of time dilation $dt_{\rm obs} = (1+z)\; dt$. Consequently, one can write:

$$h(t) = \frac{\mathcal{M}_{\rm obs}}{d_L(z)}(\pi \mathcal{M}_{\rm obs} f_{\rm obs})^{2/3} \exp\left(i\, 2\pi \int^{t_{\rm obs}} f_{\rm obs}(t')dt' \right) \Theta\,, \tag{10}$$

where $d_L(z)$ is the luminosity distance to the source and $\mathcal{M}_{\rm obs} = (1+z)\; \mathcal{M}$ is the observed value of the chirp mass. The second equation (for the frequency drift) reads accordingly:

$$f_{\rm obs}(t_{\rm obs}) = \frac{1}{\pi \mathcal{M}_{\rm obs}} \left(\frac{5}{256} \frac{\mathcal{M}_{\rm obs}}{t_{0,obs} - t_{\rm obs}} \right)^{3/8} . \tag{11}$$

Let us notice that the observed chirp mass is equal to the intrinsic chirp mass multiplied by $(1+z)$ where z is the redshift of the source. Observations of binary pulsars 1913+16 and 1534+12 as well as X-ray observations have strongly indicated that the mass distribution of NS in binaries is sharply peaked around 1.4 $M_\odot$ [23]. This coincidence suggests that natural formation mechanisms are much more restrictive for NS masses than the limitations due to nuclear equation of state. This suggestion is also supported by the theoretical studies of supernova core collapse [27]. Assuming equal mass binary this would mean that one can (in first approximation) take the distribution of intrinsic chirp mass as $\mathcal{P}(\mathcal{M}) \approx \delta(\mathcal{M} - 1.2\ M_\odot)$. It is a very fortunate circumstance in the context of potential utility of gravitational wave observations. Namely, if one detects an event with a chirp mass significantly exceeding the "canonical" value of 1.2 $M_\odot$ then this excess can be translated into redshift of the source $z = \frac{M_{\rm obs}}{1.2\ M_\odot} - 1$. Therefore, one sees that the catalogues of inspiral events seen in gravitational wave experiments contain the same information as optical redshift surveys of standard candles (like SN Ia). In fact the sharp mass distribution of NS makes NS–NS binaries the effective "standard candles" of gravitational wave astronomy.

The above discussion contained the main ideas. In reality the situation is slightly more complicated since in practice we should not expect actual waveforms to be detected. The gravitational wave detection technique is essentially the extraction of a very weak signal from the overwhelming detector noise. Of course, the knowledge of expected pattern of the waveform (the template) is crucial for the so called matched filtering method, but the direct observable quantity (deciding of whether the signal is present or not) would be the so called signal-to-noise ratio ρ. The gravity wave detector would register only those inspiral events for which the signal-to-noise ratio exceeded certain threshold value ρ_0.

For a given detector and a source the signal-to-noise ratio reads [25]:

$$\rho(z) = 8\Theta \frac{r_0}{d_L(z)} \left(\frac{\mathcal{M}(z)}{1.2\, M_\odot} \right)^{5/6} \zeta(f_{\rm max}) \,, \tag{12}$$

where $\zeta(f_{\rm max})$ is a dimensionless function describing the overlap of the signal with detector's bandwidth and r_0 is a characteristic distance scale, depending on detector's sensitivity, given by the formula:

$$r_0^2 = r_{g\odot}^2 \frac{5}{132\pi} \left(\frac{243}{7\ 10^5} \right)^{1/3} \int\limits_0^\infty \frac{(\pi r_{g\odot})^2\ df}{(\pi r_{g\odot}\ f)^{7/3}\ S_h(f)} \,, \tag{13}$$

where $r_{g\odot} = GM_\odot/c^2$ is the gravitational radius for a solar mass object, $S_h(f)$ is the detector's noise spectral power. For advanced LIGO detectors

$r_0 \approx 355$ Mpc. It has been argued that $\zeta(f_{\max}) \approx 1$ for LIGO/VIRGO interferometers [22, 25]. The relative orientation of the binary with respect to the detector is described by the factor Θ. This complicated quantity cannot be measured nor assumed *a priori*. However, its probability density averaged over binaries and orientations has been calculated [25] and is given by a simple formula:

$$
\begin{aligned}
P_\Theta(\Theta) &= 5\Theta(4-\Theta)^3/256, \qquad \text{if} \quad 0<\Theta<4\,,\\
P_\Theta(\Theta) &= 0, \qquad \text{otherwise}\,.
\end{aligned} \tag{14}
$$

To conclude these general remarks: the observed signal-to-noise ratio ρ informs us about the luminosity distance $d_L(z)$ to the source (in combination with $\mathcal{M}_{\rm obs}$) whereas the observed frequency drift $f_{\rm obs}(t)$ allows to disentangle the observed chirp mass.

Let us now assume that we have a catalogue (large enough to make statistical inference therefrom) of inspiral events for which ρ and $\mathcal{M}_{\rm obs}$ are known. The question is what are the relevant observables from which to extract the information about the cosmological model of the Universe and how sensitive they are with respect to the quintessential equation of state. The next two subsections will be devoted to this question. In the first of them we will review recently published results [18] in the second we will extend this discussion to more general case of w dependent on redshift.

3.1. Cosmic equation of state — constant w models

Let us denote by $\dot{n}_0$ the local binary coalescing rate per unit comoving volume. One can use "the best guess" for local rate density $\dot{n}_0 \approx 9.9\ h\ 10^{-8}\ \ {\rm Mpc}^{-3}{\rm yr}^{-1}$ as inferred from the three observed binary pulsar systems that will coalesce in less than a Hubble time [28]. Source evolution over sample is usually parametrized by multiplying the coalescence rate by a factor $\eta(z) = (1+z)^D$, *i.e.* $\dot{n} = \dot{n}_0\ (1+z)^2\ \eta(z)$ where the $(1+z)^2$ factor accounts for the shrinking of volume with z and the time dilation of burst rate per unit time. In order to contemplate the source evolution effects it is worth noticing that the inspiral NS–NS binaries might be the progenitors of the Gamma-Ray Bursts (GRBs). The cosmological origin of GRBs has been confirmed since discoveries of optical counterpart of GRB 970228 [29] and the measured emission-line redshift of $z = 0.853$ in GRB 970508 [30]. It has also been known for quite a long time that cosmological time dilation effects in BATSE catalogue suggest that the dimmest sources should be located at $z \approx 2$ [31]. Consequently, several authors tackled the question of source evolution in the context of gamma-ray bursts. Early estimates of Dremer [32] and Piran [33] indicated that BATSE data could accommodate quite a large range of source density evolution (from moderate negative to positive one).

Later on Totani [34] considered the source evolution effects and based his calculations on the realistic models of the cosmic star formation history in the context of NS–NS binary mergers. Comparison of the results with BATSE brightness distribution revealed that the NS–NS merger scenario of GRBs naturally leads to the rate evolution with $2 \leq \beta \leq 2.5$. In [18] the source evolution effects have been taken into account. However, the NS–NS merger scenario is by no means the unique explanation of gamma-ray bursts. Recently, the so called collapsar model became popular [35]. The idea that at least some of gamma-ray bursts are related to the deaths of massive stars is supported by the observations of afterglows in GRB 970228 and GRB 980326 [36]. Therefore, no specific value of evolution exponent D was preferred but instead it has been illustrated how strongly and in which direction does the source evolution affect our ability to discriminate between different quintessential equations of state.

The rate $\dfrac{d\dot{N}(>\rho_0)}{dz}$ at which we observe the inspiral events that originate in the redshift interval $[z,\ z+dz]$ is given by:

$$\frac{d\dot{N}(>\rho_0)}{dz} = \frac{\dot{n}_0}{1+z}\,\eta(z)\;4\pi r(z)^2\frac{dr(z)}{dz}\;C_\Theta(x)\,, \tag{15}$$

where $C_\Theta(x) = \int_x^\infty P_\Theta(\Theta)d\Theta$ denotes the probability that given detector registers inspiral event at redshift z_s with $\rho > \rho_0$. The quantity $C_\Theta(x)$ can be calculated as

$$\begin{aligned} C_\Theta(x) \;&=\; \frac{(1+x)(4-x)^4}{256} \qquad \text{for } 0 \leq x \leq 4 \\ &\quad\; 0 \qquad \text{for}\,, \quad x > 4\,, \end{aligned} \tag{16}$$

where [37]

$$x = \frac{4}{h\,A}(1+z)^{7/6}\left[\frac{d_A(z)H_0}{c}\right] \tag{17}$$

and

$$A := 0.4733\;\left(\frac{8}{\rho_0}\right)\left(\frac{r_0}{355\ \mathrm{Mpc}}\right)\;\left(\frac{\mathcal{M}_0}{1.2\ M_\odot}\right)^{5/6}\,. \tag{18}$$

The method of extracting the cosmological parameters advocated by Finn and Chernoff [25] makes use of the redshift distribution of observed events in a catalogue composed of observations with the signal-to-noise ratio greater than the threshold value ρ_0. Therefore, it is important to find this distribution function for different quintessence models. The formula for the expected distribution of observed events in the source redshift can be easily obtained from the equation (15):

$$\begin{aligned} P(z, > \rho_0) &= \frac{1}{\dot{N}(> \rho_0)} \frac{d\dot{N}(> \rho_0)}{dz} \\ &= \frac{4\pi c}{h\dot{N}(> \rho_0)} \frac{\dot{n}_0}{1+z} \eta(z) \frac{r(z)^2}{H(z)} C_\Theta(x) , \end{aligned} \tag{19}$$

where h denotes the dimensionless Hubble constant ($H_0 = h \times 100$ km/sMpc).

In [18] the following cosmological models have been explored:

$$(\Omega_0, \ \Omega_Q) = \{(0.2, 0.8); \ (0.3, 0.7); \ (0.4, 0.6)\}$$

with the w coefficient equal to

$$w = \{0, -0.2, -0.4, -0.6, -0.8, -1.\}$$

and evolutionary exponents: $D = \{-1., -0.5, 0., 0.5, 1\}$. Equations (15) and (19) have been integrated numerically.

The results can be summarized in the following way [18]:

1. Different quintessential cosmologies (singled out by w parameter in the equation of state) give negligibly small differences in predictions for annual inspiral event rate to be observed by future interferometric experiments.

2. There exists similar degeneracy in terms of cosmological models (labeled by the value of Ω_0 and Ω_Q).

3. The magnitudes of observed event rates for different evolutionary exponents D are clearly distinct, at least for the range of the Hubble constant suggested by independent cosmological evidence.

4. There is a noticeable difference in predicted event redshift distribution functions $P(z, > \rho_0)$ for different values of the cosmic equation of state within given cosmological model (labeled by the values of Ω_0 and Ω_Q).

5. The spread between different cosmological models for a given quintessence equation of state is much smaller.

6. The spread of redshift distribution functions attributed to evolutionary effects is also smaller than that caused by differences in w and has a slightly different character. This may to some extent mimic the effect of cosmic equation of state, but it should in principle be possible to disentangle — at least to a certain degree from the complementary information about the detection rates.

3.2. Cosmic equation of state — more general models

As alluded to earlier (see the Introduction) if we think that the quintessence has its origins in the evolving scalar field, it would be natural to expect that w coefficient should vary in time either, *i.e.* $w = w(z)$. An arbitrary function $w(z)$ can be Taylor expanded $w(z) = \sum_{i=0}^{\infty} w_i z^i$. Bearing in mind that both SN Ia surveys or gravitational wave observations of inspiral events are able to probe the range of small and moderate redshifts it is sufficient to explore first the linear order of this expansion. Such possibility $w(z) = w_0 + w_1 z$ has already been considered in the literature [38, 39]. Of course, more precise suggestions concerning admissible ranges of w_0 and w_1 could come from the knowledge of the ultimate model (*e.g.* the precise form of the scalar field potential) underlying the quintessence. Unfortunately, such a theory is not available, yet. Therefore, guided by cases contemplated in the literature [38, 39] we made the following assumptions $-1.1 \leq w_0 \leq -0.5$ and $-1.1 \leq w_1 \leq 1.5$. The formula (4) reads now:

$$H^2(z) = H_0^2 \left(\Omega_m \, (1+z)^3 + \Omega_Q \, (1+z)^{3(1+w_0-w_1)} \, \exp(3w_1 z) \right) \tag{20}$$

and all subsequent formulae (5), (6), (15) and (19) are modified accordingly.

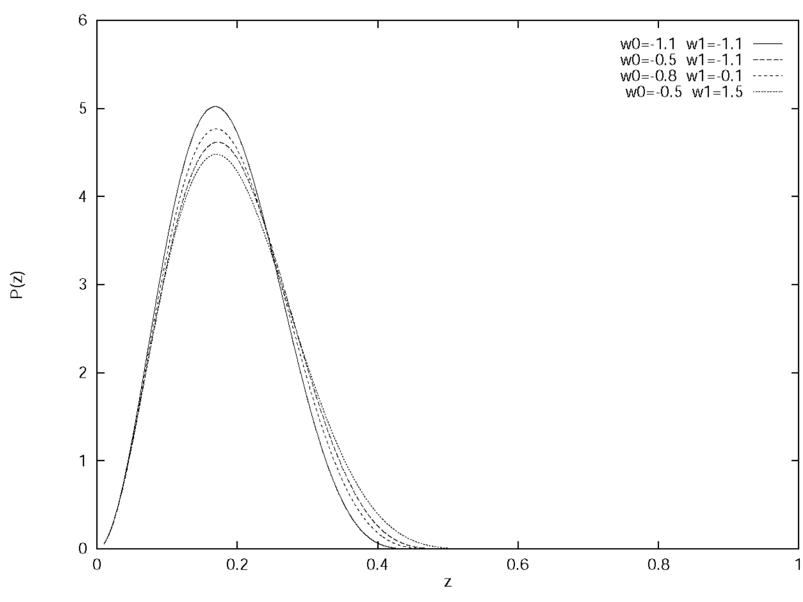

Fig. 1. Redshift distribution of observed events in the cosmological model with $\Omega_0 = 0.3$, $\Omega_Q = 0.7$ for different values of w_0 and w_1 coefficients in the z varying quintessential equation of state $w(z) = w_0 + w_1 z$.

The results of numerical integration of the formula (19) for the quintessence with z–varying equation of state $w(z) = w_0 + w_1 z$ are shown in figure 1. Displayed four different combinations of w_0 and w_1 exhibit noticeably different redshift distribution functions $P(z, > \rho_0)$. It is very promising as far as cosmological applications of the gravitational wave experiments are concerned. However, a closer inspection of Fig.1 and analogous figure obtained in [18] for quintessence models with constant w reveal that similar patterns as those obtained for different combinations of w_0 and w_1 can be reproduced in constant w models. On one hand, it carries a quite obvious message that more detailed theoretical foundations of the quintessential Universe are desired. On the other hand, complementary information obtained from other studies could be helpful anyway. For example, let us for a moment suppose that we had a catalog of inspiraling events and that the best fit $P(z, > \rho_0)$ curve for this catalog is the upper curve of the figure 1. It would mean that either we have a varying w quintessential Universe with $w_0 = -1.1$ and $w_1 = -1.1$ or $w = 0$ in the case of constant w [18]. However, the latter possibility is already ruled out since the constraints from large scale structure and cosmic microwave background anisotropies provided $-1. \leq w < -0.6$ as the 95% confidence interval estimates for constant w models [40,41]. In conclusion, we may expect fascinating new opportunities for alternative tests of cosmological models in general, and in the context of quintessence in particular when the advanced gravitational wave experiments begin to load us with the data.

4. Conclusions

Determining the nature of the quintessence — the mysterious form of the dark energy which contributes to 70% of the matter-energy of the Universe and causes it to accelerate is one of the most important problems in modern cosmology. Although, the literature concerning toy models qualitatively reproducing the main features of the quintessence is abundant, theoretical guidance to its precise form is very poor. Therefore, we need additional inspiration from observations. Probes of low redshift Universe (SN Ia) seem more promising in this respect since they are most sensitive to w between $z \approx 0.2$ and $z \approx 2$. The new class of tests making use of catalogues of inspiral events seen in gravitational wave detectors discussed in this paper will be a valuable tool for determining the details of theoretical model of our Universe. The utility of these experiments lies in the fact that luminosity distances $d_L(z)$ to the sources (extracted from the signal-to-noise ratios) and the redshifts z (extracted from the observed chirp masses) are direct observables. Hence the perspectives of gravitational wave observations are indeed fascinating and go beyond studying the sources themselves but they offer possibilities to gain information about the Universe as a whole.

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